

Dependence of asymmetries for charge distribution with respect to the reaction plane on initial energy in heavy ion collisions

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In the paper two combinations of correlators are defined in order to investigate the evolution of possible \mathcal{P}/\mathcal{CP} invariance violation in strong interactions with initial energy for heavy ion collisions. These combinations correspond to absolute and relative asymmetry of distribution of electrically charge particles with respect to the reaction plane in heavy ion collisions. Energy dependence of parameters under study was derived from data of STAR and ALICE experiments. Significant decreasing both absolute and relative asymmetry is observed at energies $\sqrt{s_{NN}} < 20$ GeV. This feature agrees qualitatively with other results of stage-I beam energy scan program in STAR experiment. General behavior of dependence of absolute asymmetry on initial energy agree reasonably with behavior of similar dependence of Chern–Simons diffusion rate calculated at different values of external Abelian magnetic field. The observed behavior of parameters under study vs energy can be considered as indication on possible transition to predominance of hadronic states over quark-gluon degrees of freedom in the mixed phase created in heavy ion collisions at intermediate energies.

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I. INTRODUCTION

The vacuum of quantum chromodynamics (QCD) is a very complicated matter, made of strongly interacting fermionic and gauge fields, with rich geometry structure. This structure can corresponds to the fractal geometry [1]. Hypothesis concerned on complex and highly irregular geometry of QCD vacuum in Euclidean space does not contradict both lattice calculations [2, 3] and fractal-like approximation of structures in distributions of topological charge density [4]. There is a fundamental interrelation between geometry and fundamental properties of QCD Lagrangian. Vacuum of QCD as non-Abelian gauge theory contains topologically non-trivial configurations of gauge fields which deeply relate with \mathcal{P}/\mathcal{CP} invariance of strong interactions. The non-trivial topology of QCD vacuum opens the possibility for existence of metastable domains which possess of various properties with respect to the discrete \mathcal{P}/\mathcal{CP} symmetries. According to predictions of the theory at finite temperature [5] decays of such domains or classical transitions (sphalerons) between them in deconfinement phase of color charges with restored chiral symmetry can result in local topologically induced violation of \mathcal{P}/\mathcal{CP} invariance in strong interactions – $lTIP$ effect. The one of possible mechanisms for manifestation of such domains and local TIP violation experimentally is the azimuthal asymmetry of distribution of electric charges in final state driven by an external Abelian magnetic field – the so called chiral magnetic effect – $\mathcal{CM}\mathcal{E}$ [6]. Experimentally charge-separation effect in relativistic heavy ion collisions was observed by STAR collaboration at RHIC for the first time [7] and was confirmed in further by ALICE collaboration at LHC [8]. As indicated above deconfinement state of color charges and restored chiral symmetry are essential for the experimental manifestation of possible local strong \mathcal{P}/\mathcal{CP} violation, i.e. for $\mathcal{CM}\mathcal{E}$. The former is needed to separate (anti-)quarks with opposite electric charges by a distance larger than nucleon size. The restored chiral symmetry is required because charge separation is possible at conserved chirality only. Therefore the investigation of energy dependence of $\mathcal{CM}\mathcal{E}$ via definition of convenient parameters and analysis of its corresponding dependence is important challenge for study of strongly interacting matter under extreme conditions and search for transition domain from prevalence of hadronic states to domination of deconfinement phase of quarks and gluons. At present the gauge-string duality seems one of the most powerful and promising tools for study of various aspects of heavy ion collisions in strong coupling regime [9]. Thus the some approaches based on the gauge-string duality can be useful for qualitative study of electric charge separation with respect to the reaction plane which is non-perturbative phenomenon.

The paper is organized as follows. In Sec.2, definitions of collective variables (correlators) and asymmetries are described. The Sec.3 devotes discussion of energy dependence of introduced asymmetries, comparison of its experimental values with approximations based on equation for Chern–Simons diffusion rate at various strengths of external Abelian magnetic field. Some final remarks are presented in Sec.4.

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II. METHOD AND VARIABLES

With taking into account possible local strong \mathcal{P}/\mathcal{CP} violation the invariant distribution of final state particles with certain sign of electric charge α ($\alpha = +, -$) can be written as following

$$E \frac{d^3 N_\alpha}{d\vec{p}} = \frac{1}{2\pi} \frac{d^2 N_\alpha}{p_\perp dp_\perp dy} \left[1 + \sum_{n=1}^{\infty} 2 \{v_{n,\alpha} \cos(n\Delta\phi) + a_{n,\alpha} \sin(n\Delta\phi)\} \right].$$

Here $\Delta\phi \equiv \phi - \Psi_{\text{RP}}$, ϕ is an azimuthal angle of particle under study, Ψ_{RP} – azimuthal angle of reaction plane, $v_{n,\alpha}$ – collective flow of n -th order, the parameters $a_{n,\alpha}$ describe the effect of \mathcal{P}/\mathcal{CP} violation. The expectation value of $a_{n,\alpha}$ will vanish if the one-particle distributions are averaged over event sample because the distributions are averaged over many domains and direction of charge separation changes event by event due to random sign of the Chern–Simons number (N_{CS}) of the local domain [6, 7]. Therefore it should be emphasized that the $\mathcal{CM}\mathcal{E}$ is the collective effect and its investigation is possible via correlation analysis only. According to the theory, the correlator contained the contribution of possible \mathcal{P}/\mathcal{CP} violation effect only is given by equation $\langle \mathbf{K}_{n,\alpha\beta}^{\text{T}} \rangle = \langle a_{n,\alpha} a_{n,\beta} \rangle$, where α, β – the electric charge signs of secondary particles. Only the first harmonic coefficient was analyzed so far because as expected the $a_{1,\alpha}$ accounts for most of the effect under study [7]. Thus the following notation $\langle \mathbf{K}_{1,\alpha\beta}^{\text{T}} \rangle \equiv \langle \mathbf{K}_{\alpha\beta}^{\text{T}} \rangle$ is used below. Experimental correlator had been proposed in [10] and it had been defined as following $\langle \mathbf{K}_{\alpha\beta}^{\text{E}} \rangle = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\text{RP}}) \rangle$. This observable is sensitive to the effect of possible local strong \mathcal{P}/\mathcal{CP} violation and measures the charge separation with respect to the reaction plane. Both theoretical and experimental correlators are averaged over pairs of particles under study in event and over all events in sample. It should be mentioned that correlators defined above are \mathcal{P} -even quantities therefore the $\langle \mathbf{K}_{\alpha\beta}^{\text{E}} \rangle$ may contains contributions from background effects unrelated to possible local strong \mathcal{P}/\mathcal{CP} violation. Theoretical and experimental correlators are related by following equation

$$\langle \mathbf{K}_{\alpha\beta}^{\text{E}} \rangle = [\langle v_{1,\alpha} v_{1,\beta} \rangle_{\text{even}} + \Delta\Phi] - \langle \mathbf{K}_{\alpha\beta}^{\text{T}} \rangle. \quad (1)$$

Here $v_{1,\alpha}$ is the directed flow parameter, $\Delta\Phi \equiv \Phi_{\text{in}} - \Phi_{\text{out}}$ – the difference between background contribution of the in-plane correlations (Φ_{in}) and background contribution of the out-of-plane correlations (Φ_{out}). Dependence of v_1 on pseudorapidity can be generally separated into rapidity-odd and rapidity-even component. The experimental contribution given by odd part of the term $\langle v_{1,\alpha} v_{1,\beta} \rangle$ on r.h.s. of (1) be neglected [7, 10, 11] because usual directed flow averages to zero at rapidities symmetric with respect to midrapidity region which is considered in most relativistic heavy ion experiments [7, 8]. The rapidity-even v_1 is originated from the dipole asymmetry of the nuclear overlap which is result of fluctuations of the initial geometry [12, 13]. The analysis of experimental data at $\sqrt{s_{\text{NN}}} = 200$ GeV supports the existence of a sizable rapidity-even v_1 [14]. These results were confirmed by further investigations at the same energy [15] as well as for highest available collision energy $\sqrt{s_{\text{NN}}} = 2.76$ TeV [16, 17]. This new type of directed flow results in nonzero contribution at averaging on rapidity symmetric region.

In the framework of $\mathcal{CM}\mathcal{E}$ model [6] the theoretical correlator is given by

$$\begin{aligned} \langle \mathbf{K}_{\alpha\beta}^{\text{T}} \rangle &= \frac{\pi^2 \langle \Delta_\alpha \Delta_\beta \rangle}{16 \langle N_\alpha N_\beta \rangle} \\ &= \frac{\kappa \alpha_{\text{S}}}{\langle N_\alpha N_\beta \rangle} \left(\frac{\pi R}{2} \sum_f q_f^2 \right)^2 \varepsilon_{\alpha\beta} \int_{S_\perp} d^2 x_\perp \xi_{\alpha\beta}(x_\perp) \int_{\tau_i}^{\tau_f} d\tau \tau [eB(\eta, \tau)]^2. \end{aligned} \quad (2)$$

Here $\varepsilon_{\pm\pm} = -0.5\varepsilon_{\pm\mp} = 0.5$, $\xi_{\pm\pm}(x_\perp) \equiv \sum_{i=+,-} \xi_i^2(x_\perp)$, $\xi_{\pm\mp}(x_\perp) \equiv \prod_{i=+,-} \xi_i(x_\perp)$, α_{S} – renormalized strong coupling constant, N_α – multiplicity of particles with electric charge sign α in event, R – radius of colliding nuclei, q_f – electric charge (in units of e) of quark with flavor f , Δ_α is the difference between total charges with fixed sign α on each side of the reaction plane, numerical coefficient $\kappa \sim 1$, x_\perp – position of nucleon from one of the colliding nuclei in the plane perpendicular to the beam axis, S_\perp – area of overlap region of colliding nuclei in the transverse plane, τ – proper time, B – strength of external Abelian magnetic field, functions $\xi_\pm(x_\perp)$ take into account the suppression effect for transitions with change of Chern–Simons number in various parts of the volume of created hot matter [6, 11]. Analytic approaches for (2) corresponded to various scenarios of initial time and comparison with STAR results were discussed early in elsewhere [11]. The most significant discrepancy between experimental and phenomenological results observed for semi-central collisions [11] requests the additional quantitative study and clear explanation. The STAR results for azimuthal correlations of high p_{T} particles with respect to the reaction plane [18] show that difference between such correlations is largest for semi-central collisions. Possibly, similar conclusion is valid for particles with moderate p_{T} too. Thus at qualitative level one can suggests that second term $\Delta\Phi$ in r.h.s. of

(1) can influences on $\langle \mathbf{K}_{\alpha\beta}^E \rangle$ and results in the additional disagreement between experimental and phenomenological data points.

In the framework of $\mathcal{CM}\mathcal{E}$ model [6] for ideal case of chiral limit and an extremely large magnetic field the average square of charge difference (in units of e) between opposite sides of the reaction plane can be estimated as following

$$\langle Q^2 \rangle = 4 \langle \Delta_t^2 \rangle \left[\sum_f |q_f| \right]^2, \quad (3)$$

where Δ_t is the difference between the number of raising and lowering of Chern–Simons number transition [6]. Let ΔN_{CS} be a total change of Chern–Simons number, which is dominated by the rate of corresponding change. In this paper it has been suggested that at finite temperature (T) the transition rate between vacuum states with different N_{CS} is dominated by transition rate due to sphalerons only, without consideration of exponentially suppressed transitions due to instantons. But it would be mentioned that some additional study and justification may be required for this approach, especially in temperature range $T_c < T < 3T_c$ [19], where T_c – temperature of phase transition to the deconfinement state of color charges. It seems temperatures reached experimentally in relativistic heavy ion collisions are in the range indicated above for present and even future colliders. Thus it is suggested that the rate of change of N_{CS} is the classical transition rate, i.e. the Chern–Simons diffusion rate (Γ_{CS}). One can suggest $\Delta_t \simeq \Delta N_{\text{CS}}$ because the most probable transitions are those which connect two neighboring vacua and transitions with simultaneously changing of absolute value of Chern–Simons number larger than on unit are suppressed [6]. By definition the Γ_{CS} quality is the probability of Chern–Simons number changing process to occur per unit 3-dimensional volume and per unit time: $\Gamma_{\text{CS}} = \lim_{V \rightarrow \infty} V^{-1} \langle [\Delta N_{\text{CS}}]^2 \rangle$, where V is the 4-dimensional volume. The parameter Γ_{CS} has been intensively studied in the framework of electroweak theory. The Chern–Simons diffusion rate was computed for weak coupling domain. The holographic AdS/CFT correspondence [20] makes it possible to derive this parameter in $\mathcal{N} = 4$ supersymmetric Yang–Mills (SYM) plasma for limit of large number of colors ($N_c \rightarrow \infty$) in the strong coupling regime [21]. Then with taking into account the sphaleron approach the Chern–Simons diffusion rate in absent of external Abelian magnetic field can be given by

$$\Gamma_{\text{CS}}^{B=0} = f(\chi) T^4, \quad f(\chi) = \begin{cases} -k\chi^5 \ln \chi, & \text{at } \chi \ll 1, \\ \chi^2/(256\pi^3), & \text{at } \chi \gg 1. \end{cases}$$

Here $\chi \equiv g^2 N_c$ is the 't Hooft effective coupling, g – gauge constant, the $\chi \ll 1$ corresponds to the weak coupling domain and $\chi \gg 1$ – to the strong coupling regime [21]. The latter corresponds to the relativistic heavy ion collisions because the created matter seems strongly correlated system. Numerical (large) coefficient k is of nonperturbative nature and can be found by a lattice simulation. Estimations demonstrate that the $k \sim 10$ for SU(2) [22] and $k \sim 10^2$ for SU(3) [23], i.e. $k \sim 10^{N-1}$ for SU(N) with $N = 2, 3$. Thus $\Gamma_{\text{CS}}^{B=0} \propto T^4$. In accordance with general definition of Γ_{CS} and (3) one can obtain $\langle Q^2 \rangle \propto \Gamma_{\text{CS}}$. One the other hand in the most ideal case under study, i.e. for contribution of the lowest Landau level only, one can derive

$$|\langle \Delta_{\pm} \Delta_{\pm} \rangle \mp \langle \Delta_{\pm} \Delta_{\mp} \rangle| = \varphi \langle [\Delta N_{\text{CS}}]^2 \rangle, \quad \varphi \equiv \frac{1}{2V} \left[\sum_f |q_f| \right]^2 \int_V d^4x [\xi_{-}(x_{\perp}) \pm \xi_{+}(x_{\perp})]^2.$$

The choice of difference of correlators in l.h.s. of the first relation seems reasonable in order to corresponding quality be positive, then

$$\langle \mathbf{K}_{\pm\pm}^T \rangle - \langle \mathbf{K}_{\pm\mp}^T \rangle \propto \langle [\Delta N_{\text{CS}}]^2 \rangle \propto \Gamma_{\text{CS}}. \quad (4)$$

Taking into account the (1) one can define the following quantity

$$A_a = -[\langle \mathbf{K}_{\pm\pm}^E \rangle - \langle \mathbf{K}_{\pm\mp}^E \rangle], \quad (5)$$

which is absolute asymmetry for azimuthal distribution of electric charges in final state and can be suggested for experimental estimation of $\langle [\Delta N_{\text{CS}}]^2 \rangle$. The relative asymmetry parameter for azimuthal distribution of electric charges with respect to the reaction plane in event is defined as following

$$A_r = \frac{|\langle \mathbf{K}_{\pm\pm}^E \rangle| - |\langle \mathbf{K}_{\pm\mp}^E \rangle|}{|\langle \mathbf{K}_{\pm\pm}^E \rangle| + |\langle \mathbf{K}_{\pm\mp}^E \rangle|}. \quad (6)$$

It should be noted that separation of possible $\mathcal{CM}\mathcal{E}$ signal from background effects is an important and difficult task for $\langle \mathbf{K}_{\alpha\beta}^E \rangle$ and consequently for both A_a and A_r quantities. The some physics backgrounds for $\langle \mathbf{K}_{\alpha\beta}^E \rangle$ were

discussed in experimental papers [7, 8]. Predictions of used event generators without incorporation of $\mathcal{CM}\mathcal{E}$ effect contradict with dependence of $\langle \mathbf{K}_{\alpha\beta}^E \rangle$ on centrality for same-charge correlations [7]. On the other hand these studies do not take into account a number of important background effects. First measurements [7] result in a wide set of background studies (see, for example, [24]). Some background correlations show the the same sign for both same sign and opposite sign pairs of particles [7, 25]. Thus one can expect that the suggested definition (5) allows to decrease contribution of some mutual backgrounds for absolute asymmetry for azimuthal distribution of electrically charged secondary particles. But the situation with total background contribution in $\langle \mathbf{K}_{\alpha\beta}^E \rangle$ is still vague. Based on the experimental results [7, 8, 26, 27] and its interpretation for wide initial energy range as well as on relations between absolute magnitudes of experimental signals and some background correlations [7] one can assume at qualitative level only that the sizable contribution in A_a and in A_r will be due to correlations driven by local \mathcal{P}/\mathcal{CP} violation in strong interactions.

III. RESULTS: ENERGY DEPENDENCE FOR ASYMMETRIES

The choice of appropriate experimentally varied parameters is crucial for study of features of phase diagram of strongly interacting matter, in particular, for search for critical point. It is important to have a control parameter whose variation changes the chemical potential μ at which the created matter crosses the transition region and freezes out. The collision energy is an such parameter because varying the collision energy has a large effect on μ at freezeout [28]. Fig. 1 shows the energy dependence of A_a for semi-central events in various bins of centrality for heavy ion beams. Absolute asymmetry values are calculated based on experimental data from [8, 26, 27]. Collisions of moderate Cu nuclei are characterized by significantly larger values of A_a than that for heavy ions (Au, U) at corresponding energies. It would be noted that for Au+Au at $\sqrt{s_{NN}} = 62.4$ and 200 GeV absolute asymmetry (5) was calculated based on the preliminary STAR correlators for increased (full) statistics at former energy and for Run 7 data sample at second initial energy [27]. These preliminary STAR results allow to decrease the divergence of experimental points and get slightly more smooth dependence A_a on $\sqrt{s_{NN}}$. The equation for Chern–Simons diffusion rate for case of finite B was derived in [29]. Background magnetic field typically created in relativistic heavy ion collisions is characterized by the strength $B \sim T^2$ [6, 11, 30]. The regime of finite external magnetic field is investigated in the paper and it is observed that the curves for $B = 0$ and for case $B \sim T^2$ coincide completely for all centrality bins under consideration, i.e. for full centrality domain 20-60% shown at Fig. 1. But relations (4) were obtained for extremely strong magnetic field. Thus energy dependence for the Chern–Simons diffusion rate are computed for external Abelian magnetic field with various strengths as following [29]

$$\Gamma_{CS}^{B \neq 0} = \Gamma_{CS}^{B=0} [1 + \zeta^2 / (6\pi^4)], \quad \zeta \equiv B/T^2.$$

It would be noted that at fixed ζ functional dependence of Γ_{CS} on T is the same both for $B = 0$ and for general case of presence of finite external Abelian magnetic field. Analytical function suggested in [31] for description of energy dependence of chemical freeze-out temperature agrees with available experimental data quite reasonable for energies up to $\sqrt{s_{NN}} = 200$ GeV [32] and for all centralities [33] under study. Therefore the analytic dependence $T(\sqrt{s_{NN}})$ from [31] is used for estimations of Γ_{CS} in energy domain under study. The smooth curves at Fig. 1 are the energy dependence of Chern–Simons diffusion rate in the strong coupling regime at $B = 0$ (solid), $B = 5T^2$ (dashed) and $B = 10T^2$ (dotted). The norm for solid curves is the STAR point for Au+Au at $\sqrt{s_{NN}} = 200$ GeV. The shaded bands for Chern–Simons diffusion rate at $B = 0$ are defined by uncertainties of T value at fixed initial energy due to errors of parameters in analytic function described of $T(\sqrt{s_{NN}})$ experimental dependence [31].

As seen, phenomenological curves $\Gamma_{CS}(\sqrt{s_{NN}})$ are in area caused by spread of T values at fixed $\sqrt{s_{NN}}$ for following wide range of changing of strength of external Abelian magnetic field $B \leq 5T^2$ at any initial energies under study, moreover at $\sqrt{s_{NN}} \lesssim 12$ GeV – for all range of changing of B under considered on Fig. 1. Functional behavior of $\Gamma_{CS}(\sqrt{s_{NN}})$ does not depend on B in high energy domain at changing of B on order of magnitude at least. On the other hand the Chern–Simons diffusion rate decreasing faster at $\sqrt{s_{NN}} \leq 30$ GeV for larger strength of external Abelian magnetic field. Possibly, the equation for Chern–Simons diffusion rate without external B is valid for any initial energies up to $\sqrt{s_{NN}} = 2.76$ TeV and for $\tau > 0.1$ fm/c due to uncertainty area for $\Gamma_{CS}(\sqrt{s_{NN}})$ at $B = 0$ discussed above and B values reached in heavy ion collisions [11]. Therefore further decreasing of uncertainties of parameters which are used for analytic approximation of $T(\sqrt{s_{NN}})$ behavior is essential for quantitative study of Γ_{CS} dependence on strength of external Abelian magnetic field in nucleus-nucleus collisions.

One sees the some decreasing of A_a for LHC energy as compared to initial energy domain $\sqrt{s_{NN}} \sim 100$ GeV, the absolute value of decreasing growths for more peripheral events. Absolute asymmetry of azimuthal distribution of electric charges in final state A_a goes down significantly with $\sqrt{s_{NN}}$ decreasing for intermediate initial energy domain 7.7 – 20 GeV in semi-central heavy ion collisions (Fig. 1). For each centrality bin under study the preliminary experimental results for $A_a(\sqrt{s_{NN}})$ correspond to the energy dependence of Γ_{CS} at $B = 0$ on qualitative level with some

enhancement of experimental points over phenomenological curves in range $\sqrt{s_{NN}} \sim 20 - 40$ GeV for events with 20-30% (Fig. 1a) and 30-40% (Fig. 1b) centrality. Perhaps, for better description of $A_a(\sqrt{s_{NN}})$ at $\sqrt{s_{NN}} \sim 20 - 40$ GeV the influence of external B on Γ_{CS} should be taken into account. This suggestion agrees with dependence of B on initial energy [11] which demonstrates that B in intermediate energy range $\sqrt{s_{NN}} \sim 20 - 40$ GeV reaches very large values with respect to the strength of B at $\sqrt{s_{NN}} \sim 100$ GeV. The qualitative agreement is observed between values of parameter (5) calculated via preliminary STAR results for Au+Au collisions and phenomenological curves for any B under consideration. This feature can be considered as some evidence of validity of equations (3) and (4) obtained at ultimate strong external Abelian magnetic field for heavy ion collisions. Decreasing of $\Gamma_{CS}(\sqrt{s_{NN}})$ observed at $\sqrt{s_{NN}} < 20$ GeV should lead to attenuation of $\mathcal{CM}\mathcal{E}$ and its manifestation on experiment at intermediate energies. Taking into account conditions which are essential for $\mathcal{CM}\mathcal{E}$ one can suppose the following hypothesis. The changing of behavior of dependence $A_a(\sqrt{s_{NN}})$ observed at transition from high energy domain down to intermediate energy range may be driven by predominance of hadronic colorless states over quark-gluon deconfinement phase at $\sqrt{s_{NN}} < 19.6$ GeV and, as consequence, by decreasing of $\mathcal{CM}\mathcal{E}$. Thus behavior of experimental parameter (5) vs collision energy agrees with qualitative expectation for transition to the predominance of hadronic phase in domain $\sqrt{s_{NN}} < 19.6$ GeV and with decreasing of Chern–Simons diffusion rate at intermediate initial energies.

Fig. 2 demonstrates the energy dependence of A_r for semi-central (20-60%) events for various ion beam collisions. Relative asymmetry values are calculated based on experimental data from [7, 8, 26, 27]. As well for Fig. 1 the dependence under study is some improved by calculations of parameter (6) based on increased STAR statistics at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. One sees the discrepancy of A_r values for moderate and heavy nuclei at same energies increases for more peripheral events. Behavior of $A_r(\sqrt{s_{NN}})$ for heavy ions changes dramatically at $\sqrt{s_{NN}} < 19.6$ GeV, especially for last three bins of centrality (Fig. 2b-d). The sharp decreasing of relative asymmetry (6) for energies indicated above can be considered, possibly, as evidence for (significant) amplification of hadronic phase influence on experimental observables. The observed feature of $A_r(\sqrt{s_{NN}})$ and above suggestion agree with other STAR results obtained in the framework of stage-I beam energy scan (BES-I) program at RHIC [26, 34].

It should be emphasized that energy dependence of parameters (5) and (6) obtained for any centralities from most central (0-5%) to most peripheral (70-80%) events are similar to them shown at Fig. 1 and Fig. 2.

IV. SUMMARY

Two asymmetry parameters are introduced in order to investigate the evolution of possible local strong \mathcal{P}/\mathcal{CP} violation in heavy ion collisions with initial energy. Dependence on $\sqrt{s_{NN}}$ has been obtained for absolute (A_a) and relative (A_r) asymmetries based on the experimental correlators. The energy dependence of absolute asymmetry for semi-central events in heavy ion collisions shows sharp decreasing at $\sqrt{s_{NN}} < 19.6$ GeV, almost constant behavior up to $\sqrt{s_{NN}} \simeq 200$ GeV with some decreasing at further energy increasing. Dependence $A_a(\sqrt{s_{NN}})$ qualitatively corresponds to the energy dependence of Chern–Simons diffusion rate in $\mathcal{N} = 4$ SYM plasma at $N_c \rightarrow \infty$ in strong coupling regime. The main features of A_r energy dependence agree with behavior of $A_a(\sqrt{s_{NN}})$ for wide energy domain under study. Thus energy dependencies of suggested asymmetry parameters with similar features at intermediate $\sqrt{s_{NN}}$ indicate possibly on the beginning of predominance of hadronic states versus phase of color degrees of freedom in deconfinement state in the matter created in heavy ion collisions with initial energies from domain $\sqrt{s_{NN}} \lesssim 11.5 - 19.6$ GeV. Therefore the asymmetry parameters and corresponding energy dependence seems to be useful for study of $\mathcal{CM}\mathcal{E}$ and transition from predominance of quark-gluon phase to hadronic one.

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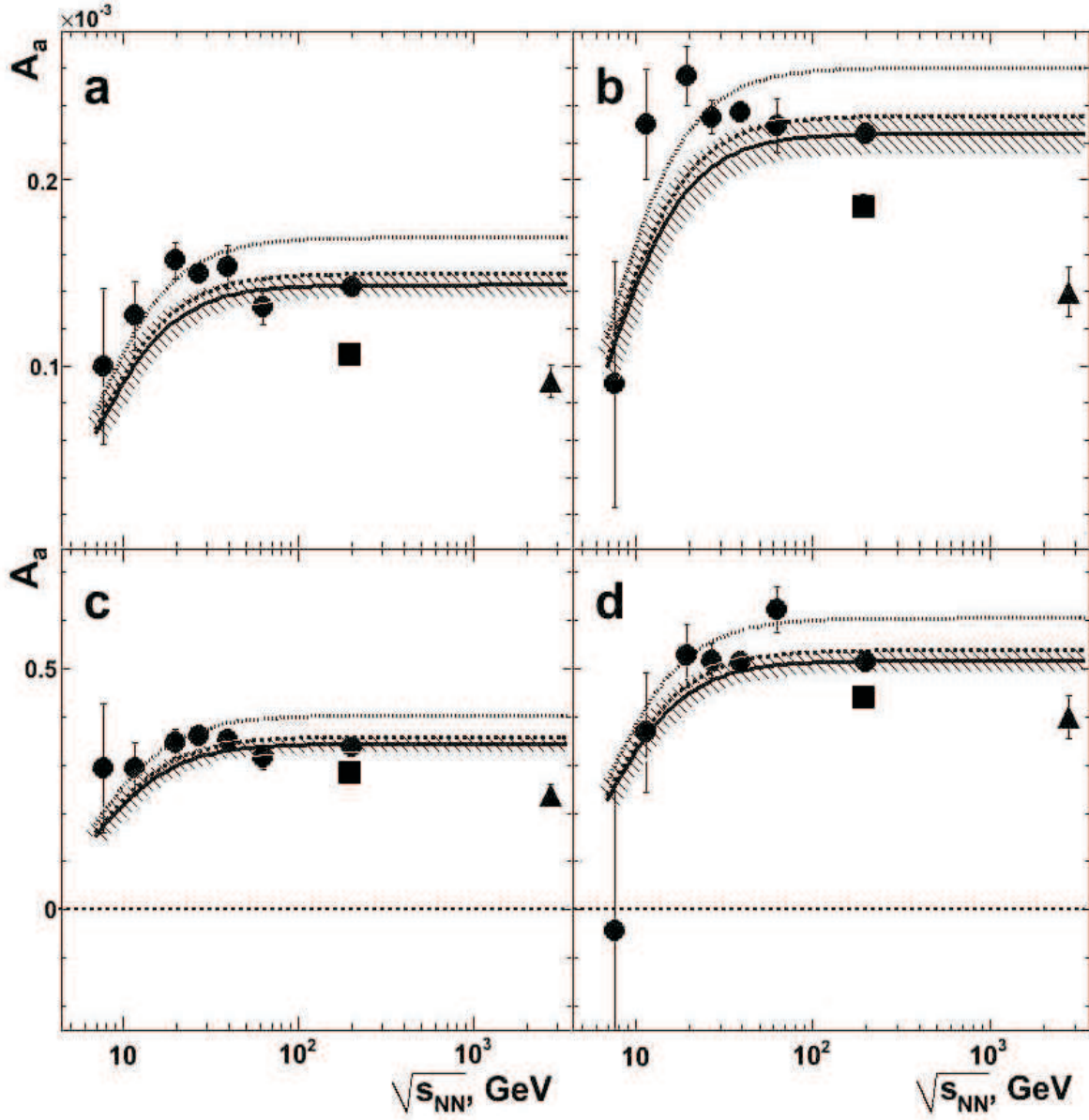


FIG. 1: Energy dependence of A_a for heavy ion collisions in various centrality bins: a – 20-30%, b – 30-40%, c – 40-50% and d – 50-60%. Experimental points are shown as following: \bullet – Au+Au, \blacktriangle – Pb+Pb and \blacksquare – U+U. Absolute asymmetry values are calculated based on experimental data from [8, 26, 27]. Smooth curves correspond to the energy dependence of Chern–Simons diffusion rate in the strong coupling regime for external magnetic field with strength $B = 0$ (solid), $B = 5T^2$ (dashed) and $B = 10T^2$ (dotted). The shaded areas for Γ_{CS} at $B = 0$ are defined by uncertainties of T value at fixed initial energy due to errors of parameters in analytic function described of $T(\sqrt{s_{NN}})$ experimental dependence [31].

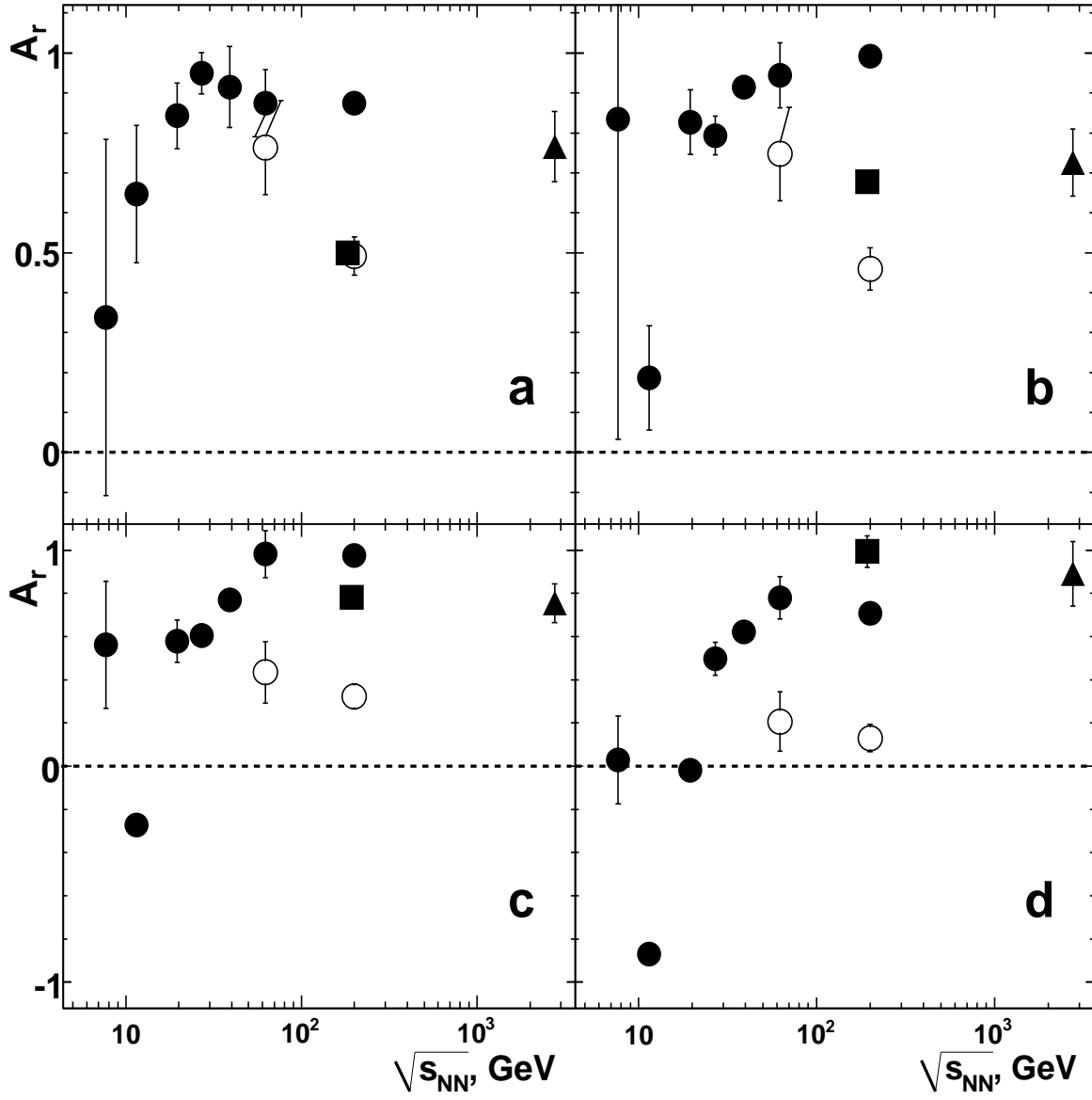


FIG. 2: Energy dependence of A_r for moderate and heavy nucleus-nucleus collisions in various centrality bins: a – 20-30%, b – 30-40%, c – 40-50% and d – 50-60%. Experimental points are shown as following: \circ – Cu+Cu, \bullet – Au+Au, \blacktriangle – Pb+Pb and \blacksquare – U+U. Relative asymmetry values are calculated based on experimental data from [7, 8, 26, 27].